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Short communication

Ventilator-derived dynamic respiratory system compliance: Comparison with static compliance in children

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ABSTRACT

Measurement of dynamic lung compliance during breathing requires measurement of esophageal pressure, whereas static respiratory system compliance (Crs) method requires several airway occlusions. Despite their precision these compliance methods are cumbersome and not suitable for evaluation of pulmonary system in intensive care. The current ventilators display dynamic Crs, which, however, is seldom utilized in clinical practice. We studied the feasibility of ventilator-derived dynamic Crs measurement in pulmonary evaluation after congenital cardiac surgery in children. In 50 children static Crs was measured by double-occlusion technique, and compared with simultaneous ventilator-derived dynamic Crs values. The early postoperative dynamic and static Crs showed a correlation ($r = 0.57$, $p < 0.0001$), but static Crs was 48% higher than dynamic ($p < 0.0001$). Dynamic Crs measurement showed no correlation with radiographic lung edema findings, whereas the static Crs showed a negative correlation with radiographic lung edema scoring ($r = -0.50$, $p = 0.0002$). Thus ventilator-derived dynamic Crs seems less reliable in postoperative pulmonary evaluation than static Crs.

1. Introduction

Lung compliance or respiratory system compliance (Crs) can be measured in static airways with halted airflow, or as dynamic compliance during breathing. Currently, the best estimate of compliance is acquired with airway occlusions for static Crs, or with esophageal pressure measurement as an estimate of pleural pressure for dynamic lung compliance measurement (Gerhardt et al., 1989; Goetz et al., 2001). However, due to their laborious and cumbersome nature, neither compliance measurement method lends itself to daily clinical practice in pediatric intensive care.

Today's modern ventilators, without measuring esophageal pressure, continuously display dynamic expiratory Crs, which has shown a strong correlation with static Crs in neonates with respiratory failure (Kugelman et al., 1995; Storme et al., 1992). Moreover, dynamic lung mechanics may be useful in optimizing ventilator management in critically ill patients (Macnaughton 2006; Stenqvist et al., 2008).

We studied the feasibility of ventilator-derived dynamic Crs measurement by comparing it with static Crs during expiration in children without respiratory failure after congenital cardiac surgery. Additionally, we studied whether early postoperative dynamic and static Crs reflect chest radiography (CXR) lung edema assessment, or short-term clinical outcome.

2. Methods

We studied 50 children 1–6 h after congenital cardiac surgery at Children's Hospital, Helsinki University Hospital (Table 1). The institution's Ethics Committee approved the study protocol, and parents provided written informed consent. The complexity of care and potential for postoperative morbidity was defined according to the Aristotle Comprehensive Complexity (ACC) score, and short-term clinical outcome was interpreted as length of mechanical ventilation and pediatric intensive care unit (PICU) stay (Table 1).

All patients had a cuffed endotracheal tube and were mechanically normoventilated with pressure-controlled synchronized intermittent mandatory ventilation (SIMV) by the SERVO-i ventilator (Maquet, Rastatt, Germany). The expiratory static Crs was measured by the double-occlusion technique (Labmanager 4–521; Erich Jaeger GmbH, Hoechberg, Germany) 1–6 h postoperatively in PICU (Goetz et al., 2001). Airflow was occluded on average for 413 ± 201 ms during the first occlusion, for 253 ± 94 ms

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Table 1
Clinical characteristics, ventilator and static Crs measurement settings.

Age [months]	4.7 (1.4–10.7)
Diagnoses with operations	
AVSD & TOF, repair	1 (2%)
CoA, repair of LVOTO	2 (4%)
Critical Pulmonary Stenosis, repair	1 (2%)
Double Aortic Arch, repair in thoracotomy	1 (2%)
Intracardiac L-R Shunt, repair by sutures or patching in ASD (2), ASD&VSD (4), AVSD (4), VSD (8)	18 (36%)
Patent Ductus Arteriosus, repair	1 (2%)
PA + VSD/TOF, repair (4), closure of residual VSD (1), LPA & RPA plasty (1)	6 (12%)
Single Ventricle; Norwood procedure (1), BDG (4), TCPC (4), PA banding (1)	10 (20%)
TAPVD, repair	1 (2%)
TGA, arterial switch operation	6 (12%)
Truncus Arteriosus, repair	2 (4%)
RVOTO & SVAS, repair of RVOTO by resection and SVAS by patch augmentation	1 (2%)
Aristotle comprehensive complexity score	8.8 (6.0–11.0)
Delayed sternal closure	7 (14%)
Cardiopulmonary bypass	
Perfusion time in minutes	82 (54–148)
Aortic cross-clamping in minutes	46 (16–93)
Days in PICU postoperatively	3 (2–6)
Days on mechanical ventilation	1 (0.5–3)
Ventilator settings	
PEEP	5 (5–5)
Pressure support over PEEP	14 (13–16)
SIMV frequency per minute	25 (20–30)
Tidal volume [ml]	60 (36–102)
Static Crs measurement	
First occlusion [ms]	413 ± 201
Second occlusion [ms]	253 ± 94
First pressure plateau [ms]	250 ± 120
Second pressure plateau [ms]	150 ± 70

ASD = atrial septal defect, AVSD = atrioventricular septal defect, BDG = bidirectional Glenn procedure, CoA = coarctation of Aorta, LPA = left pulmonary artery, IQR = interquartile range, L-R = left to right, PA = pulmonary atresia, PEEP = positive end expiratory pressure, PICU = pediatric intensive care unit, RPA = right pulmonary artery, RVOTO = right ventricular outflow tract obstruction, SIMV = synchronized intermittent mandatory ventilation, SVAS = supravalvular aortic stenosis, TAPVD = total anomalous pulmonary venous drainage, TCPC = total cavopulmonary connection, TGA = transposition of the great arteries, TOF = tetralogy of Fallot, VSD = ventricular septal defect
Data are presented as n (%), median with interquartile range or mean ± SD, as appropriate.

during the second occlusion, and a minimum of 10 respiratory cycles occurred between each double occlusion (Table 1). On average five static Crs values [coefficient of variation 0.06] were available for each patient. One patient's pressure-volume curves lacked acceptable pressure plateaus, thus these data were omitted from analysis. The ventilator and static Crs measurement settings are provided in Table 1. The SERVO-i calculated the expiratory dynamic Crs for each breath as follows:

$$dyn\ Crs = \frac{expiratory\ tidal\ volume}{end\ inspiratory\ pressure - end\ expiratory\ pressure}$$

This formula is comparable to multiple ventilators on market. Without airflow occlusions Servo-i measures end inspiratory pressure just before start of expiration when inspiratory airflow diminishes to almost zero, and end expiratory pressure just before start of inspiration. Thus, end expiratory pressure is close to positive end expiratory pressure (PEEP). The average value for a 15-min period coinciding with the static Crs measurement was used for analyses. The CXRs taken within 2 h of static Crs measurement were scored for lung edema on a 4-step scale (0 = normal lung, 1 = minimal opacity not obscuring lung vessels, 2 = opacity partially obscuring lung vessels, 3 = opacity totally obscuring lung vessels).

Our primary interest was to study the correlation between dynamic and static Crs. The sample size calculation based on correlations with r being up to 0.90 found in previous studies on neonates would have allowed sample size around 10 patients (Kugelman et al., 1995; Storme et al., 1992). However, we wanted to base sample size calculation on a lower correlation (r = 0.65) because we estimated lower r to be more realistic but still clinically significant. To find a correlation between 0.5 and 0.7, we needed 42 patients (based on 80% power and a two-sided test with α = 0.05) (3). Additional patients were recruited to allow for dropouts.

Variables on a qualitative scale are presented as n with percentages. Normality of variables on a continuous scale was assessed visually and by Kolmogorov-Smirnov test. Variables on a continuous scale described as mean ± SD or median with interquartile range (IQR) were compared with Student's *t* test or Mann-Whitney *U* test, as appropriate. Correlations were examined with Pearson's test and linear regression analysis or Spearman's test, as appropriate. We further analyzed difference between dynamic and static Crs by Bland-Altman method. In the Bland-Altman plot the difference of the dynamic and static Crs was plotted on y-axis against the mean of the two Crs measurements on x-axis. A p value ≤0.05 was considered significant for all statistical analyses. Statistical analyses were performed with SPSS 21.0 (IBM Corp., Armonk, NY, USA) and Prism 7.0 (GraphPad Software, La Jolla, CA, USA).

3. Results

Dynamic and static Crs demonstrated a positive correlation (r = 0.57, $p < 0.0001$) (Fig. 1A), but static Crs was 48% higher than dynamic (7.4 ± 2.4 ml/kPa/kg vs. 5.0 ± 1.4 ml/kPa/kg, $p < 0.0001$). In Bland-Altman analysis, the mean difference between static and dynamic Crs was 2.50 ml/kPa/kg (Fig. 1B).

Dynamic Crs measurement showed no correlation with CXR LE scoring, whereas static Crs showed a negative correlation (r = -0.50, p = 0.0002) (Fig. 2). Both dynamic Crs (p = 0.42) and static Crs (p = 0.17) showed no difference between patients with open or closed sternum. No significant correlations occurred between dynamic or static Crs and length of cardiopulmonary bypass (CPB), length of aortic cross-clamping, ACC score, or short-term clinical outcome interpreted as length of mechanical ventilation and PICU stay (data not shown). Both dynamic (r = 0.41, p = 0.006) and static Crs (r = 0.44, p = 0.002) correlated positively with tidal volume, but not with PEEP, pressure support over PEEP, or respiratory rate (data not shown).

4. Discussion

We found a moderate correlation between dynamic and static Crs. However, the correlation was weaker than demonstrated by previous studies on newborn infants (Kugelman et al., 1995; Storme et al., 1992). The distinction in these correlations may derive from differences in static Crs methods, and in study patients. The previous studies used single occlusion technique, which is influenced by airway and tracheal tube resistance, similarly to dynamic Crs (Kugelman et al., 1995; Storme et al., 1992). In the present study, we chose the double-occlusion technique, which calculates Crs as the difference between two occlusions' pressure-volume pairs, and is unaffected by airway resistance (Goetz et al., 2001). Furthermore, our patients without a pulmonary source for respiratory failure were homogenous in terms of their ventilatory state.

Bland-Altman analysis clearly demonstrated that dynamic and static Crs values are not equivalent. Despite correlating, dynamic Crs values were significantly lower than corresponding static Crs, which is consistent with previous studies (Kugelman et al., 1995; Stenqvist et al., 2008). These measurements may assess different phenomena, since dynamic Crs is measured during some airflow and without airflow occlusions. Thus, dynamic Crs is influenced by the effect of simultaneous

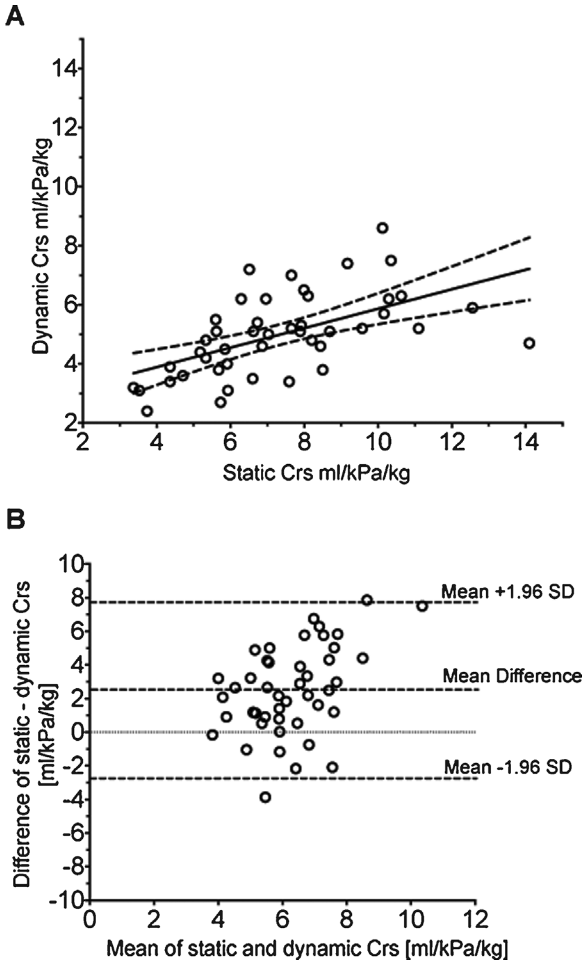

Fig. 1. During regular breathing static respiratory system compliance (Crs) correlated with simultaneously determined dynamic Crs (r = 0.57, $p < 0.0001$) (A). Dashed lines indicate the 95% confidence interval. In Bland-Altman analysis (B), the mean difference between static and dynamic Crs was 2.50 ml/kPa/kg and 95% of the differences fell between −2.71 and 7.71 ml/kPa/kg.

resistance. Furthermore, only static Crs correlated with CXR lung edema scoring. Consequently, static Crs may reflect the postoperative state of lung parenchyma and possible effect of increased extravascular lung water better than ventilator-derived dynamic Crs.

Although CPB and cardiac surgery may reduce postoperative Crs values (Lanteri et al., 1995; Polese et al., 1999), we found no correlation between Crs and length of CPB or aortic cross clamping. Neither did we find correlation between early postoperative Crs and short-term outcome. Although Crs has associated with short-term outcome in adults with acute lung injury (Seeley et al., 2011), in children undergoing congenital cardiac surgery the length of mechanical ventilation and PICU stay may be more related to multiple factors during the postoperative course (Brown et al., 2003).

In conclusion, despite reasonable correlation between the dynamic and static Crs, the values do differ, and only static Crs correlates with radiographic findings of lung edema. Therefore ventilator-derived dynamic Crs seems less reliable in assessment of postoperative lung parenchyma than static Crs.

Conflict of interest and source of funding

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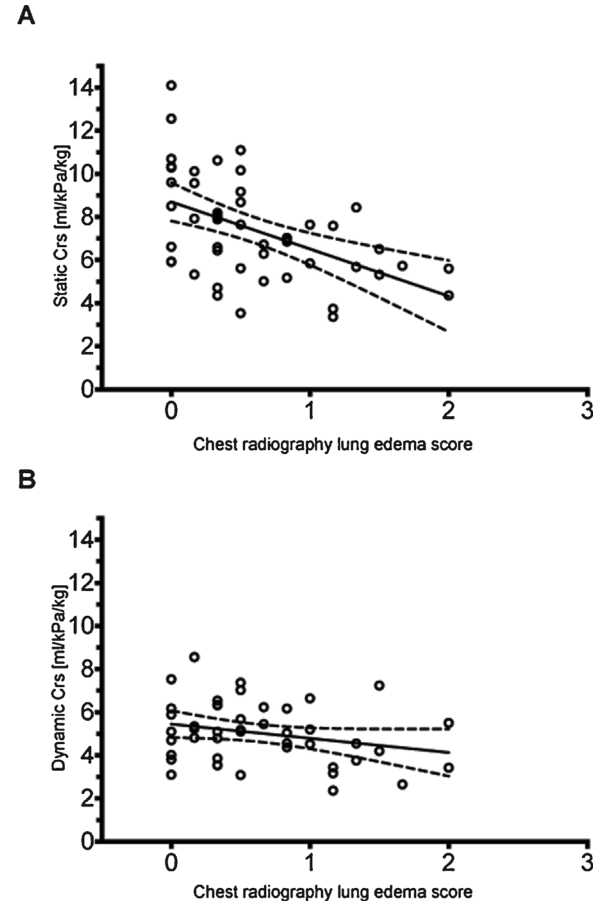

Fig. 2. Early postoperative chest radiography lung edema scoring showed a significant linear correlation with static respiratory system compliance (r = −0.50, p = 0.0002) (A), but not with dynamic respiratory system compliance (r = 0.26, p = 0.08) (B). Dashed lines indicate the 95% confidence interval.

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